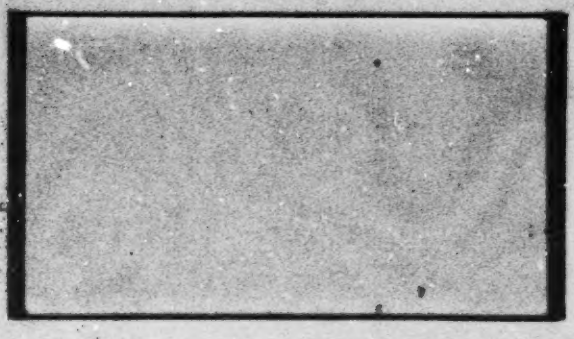

ZEROAIR
Version 1.0

User's Manual

August 1983

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1. INTRODUCTION

The ZEROAIR computer program was developed by Enermodal Engineering Limited to simulate the performance of solar space heating systems using air-based solar collectors and no storage unit. The program can accept data of all PUSH approved air-based collectors (Amherst 200, Solartech Solair, and Watershed A-100) and any other parallel plate air-based collector.

ZEROAIR is the only computer program capable of simulating zero storage air-based solar space heating systems. Performance calculations use a one-hour time step to ensure maximum accuracy.

In general, this type of system is best suited to buildings that can be allowed to fluctuate in temperature (e.g. warehouses). Buildings that require precise temperature control and have high internal heat gains during the day are not suited to this type of solar heating system. Because there is no storage of heat (other than in the building structure and its contents), the solar heating system can supply very little of the nighttime heating load. As such the system should be sized to meet under 40% of the heating load. A larger system would be inefficient and therefore expensive.

The ZEROAIR computer program will provide an accurate estimate of the thermal performance of zero storage solar space heating systems provided that the user supplies system parameters within the program limitations. All users should read and understand this manual before using the program.

2. THE ZEROAIR COMPUTER PROGRAM

2.1 System Operation

A zero storage air-based solar space heating system is shown in Figure 1. The system consists of air-based solar collectors, supply and return ductwork, fan and control system. In many cases the collectors can be mounted directly on the south wall of a building with no need for collector support racks or supply and return ductwork. If collector air is blown directly into the building it may be necessary to install a ceiling fan to mix the building air.

The control system for this type of system is quite simple. There are only two modes of operation: system on and system off. If the temperature of the collector is greater than that of the building, air is circulated through the collectors. The fan would continue to operate until the collector temperature drops below the building temperature or the maximum allowable building temperature is exceeded. On spring and fall days when the solar gain exceeds the heating load, the system will constantly cycle on and off so as not to exceed the maximum building temperature.

2.2 Using the ZEROAIR Program

Using the ZEROAIR computer program is relatively easy. The program has been written so that the user enters the system description interactively with the computer. The program makes some fundamental checks on the suitability of the input parameters. If a parameter appears unrealistic, a warning is printed although the program accepts the value.

Before the program can be run hourly weather data (solar radiation on a horizontal surface and ambient temperature) must be available. This data can be obtained from Atmospheric Environment Service. The first step in the program execution is to calculate solar radiation on the collector surface and store it in a scratch file. During the simulation the program accesses the scratch file. If collector slope and orientation remain the same on successive runs, the same scratch file is used. If the values are changed, the scratch file is automatically recalculated.

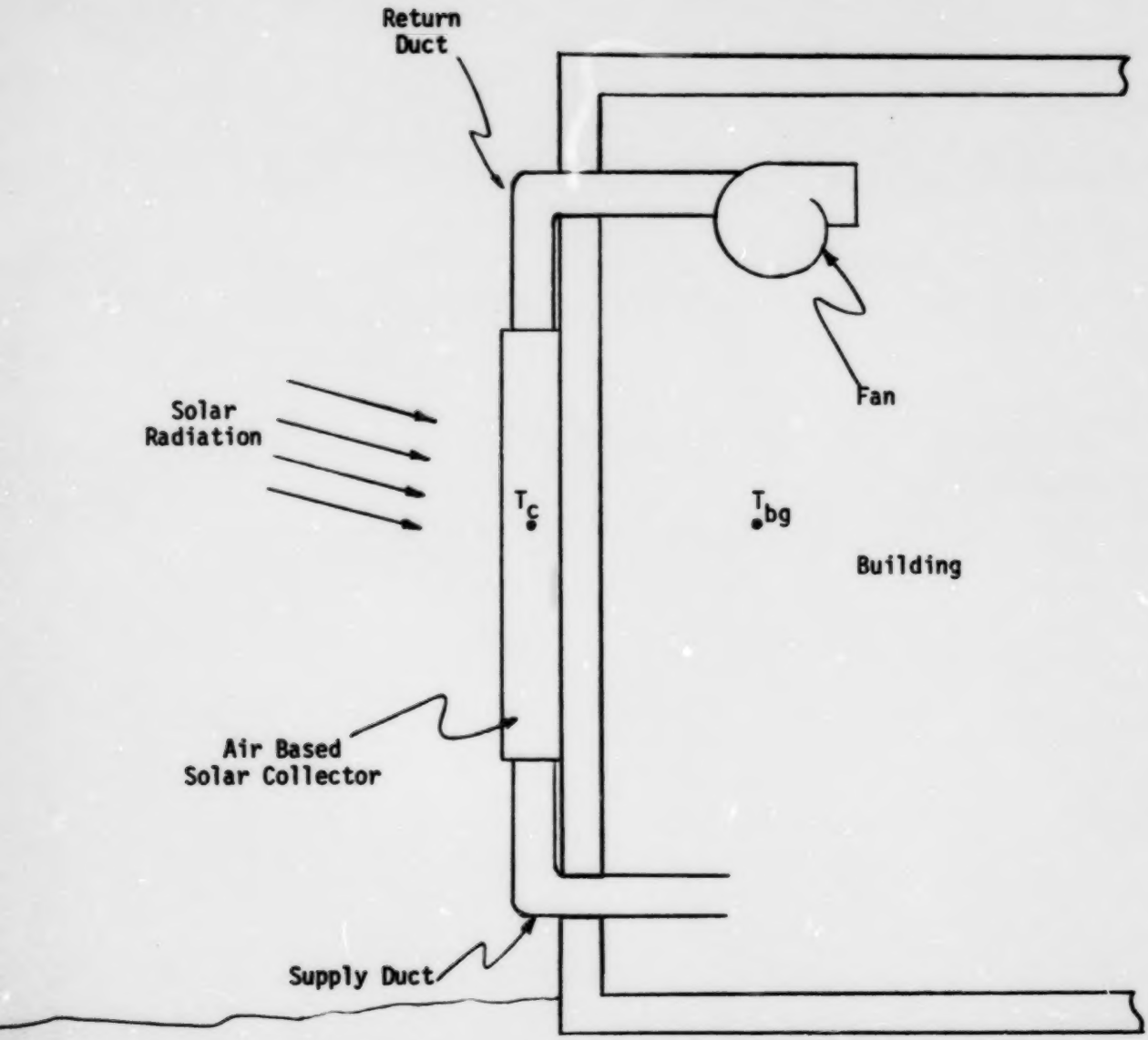


Figure 1: Zero Storage Air-Based Solar Space Heating System

When the user accesses the program, a series of questions concerning the program will have to be answered. These questions are shown in Section 2.3. When the questions have been answered, the user has the choice of several commands

C or CHANGE
D or DEFAULT
L or LIST
M or MODIFY
R or RUN
S or STOP
T or TITLE

The use of these commands is discussed below.

CHANGE this command is used to change the program input data. A list of the input data and their meanings is given in Section 3.1. The command is of the form
C or CHANGE Parameter # = New Value
e.g. C C3 = 50
Several changes can be made on one line with or without the equal sign
e.g. C C4 = 0.0, T1 3

DEFAULT this command is used to re-initialize all the input parameters to their default values. There are no options with this parameter.

LIST this command is used to list either all the input parameters, all the parameters of one section or an individual parameter.
L or LIST ALL - lists all parameters
L C - lists all collector parameters
L C3 - lists collector slope

MODIFY this command is used to modify the default collector characteristics i.e. to change the collector type.

RUN this command is used to run the program. If the option "P" is used a copy of the output will be sent to the printer. If a simulation period other than one year is required, the first day of the simulation followed by the length of the simulation should be entered
e.g. RUN or R P 31,28 - this would execute the program starting January 31st and run for 28 days. A copy of the output would be sent to the printer.

STOP this command stops the program.

TITLE this command is used to insert a title into the program output. The same title will be printed on every successive run unless it is changed

e.g. TITLE or T THIS IS RUN NUMBER 1.

2.3 Tutorial Session

3. SYSTEM INPUT PARAMETERS

The following sections describe the parameters used in the ZEROAIR computer program. The default value for each parameter is included with the definition.

3.1 Definition of Input Parameters

There are three separate sections of input data:

C - collector data
T - collector test data
L - building heating load data

The parameters for each of these sections are discussed below.

Collector Data

C1 NUMBER OF COLLECTORS (2)

The number of collectors in the solar heating system.

C2 NUMBER OF COLLECTORS IN SERIES (1)

The number of collectors that are connected in series as opposed to parallel.

C3 COLLECTOR SLOPE (DEGREES) (45)

The angle that the collector is tilted from the horizontal in degrees. This parameter must be between 0 and 90. If this parameter is different from the value on the scratch weather file, the weather data will automatically be reprocessed.

C4 COLLECTOR ORIENTATION (SOUTH=0 EAST=+, DEG) (0)

The number of degrees that the collector is oriented off due south (east is positive, west is negative). This parameter must be between -90 and 90. If this parameter is different from the value on the scratch weather file, then the weather data will automatically be reprocessed.

C5 COLLECTOR FLOW RATE PER UNIT AREA (L/(SEC*M2) (10)

The air flow rate per unit collector area through the collectors for the proposed system in litres per sec per square metre of collector.

C6 PERCENT COLLECTOR LOOP AIR LEAKAGE (5)

Percent of the collector flow rate that leaks into the collector loop (i.e. collector under negative pressure). For a collector loop under positive pressure (air leaks out) use a negative percentage. A well designed and installed system should have a leakage rate of under 10%.

C7 FAN POWER CONSUMPTION PER UNIT AREA (W/M2) (10)

The energy required to operate the collector fan in watts per square metre of collector.

Collector Test Data

The program contains test results for three air-based solar collectors (effective Jan. 24, 1983): Amherst 200, Solartech Solair and Watershed A-100. These test results can be updated or other test results added.

T1 GROSS AREA OF ONE COLLECTOR (M2) (2)

The gross or outside area of one collector in square metres.

T2 NUMBER OF COLLECTORS IN SERIES WHEN TESTED (1)

Number of collectors connected in series when it was tested, typically one.

T3 FR-TAU-ALPHA (TEST) (0.5)

The $F_R(\tau\alpha)_e$ of the collector when tested by a certified laboratory (based on gross collector area).

T4 FR-UL (W/M C) (TEST) (4.0)

The $F_R U_L$ of the collector when tested by a certified laboratory (based on gross collector area) in W/(m°C).

T5 INCIDENT ANGLE MODIFIER (-0.1)

Coefficient that reduces collector solar transmission for incident angles off the normal. The value for this coefficient, b_o, is obtainable from collector data sheets and is usually negative. If test results are not available use -0.10 for single glazed collectors and -0.17 for double glazed collectors.

T6 COLL. TEST FLOW RATE PER UNIT AREA (L/SEC*M2) (10.)

The air flow rate through the collector at test conditions in litres per second per square metre of collector.

T7 TRANSMISSION-ABSORPTION PRODUCT (0.9)

The ($\tau\alpha$) effective of the collector. This can be estimated as 1.01 times $\tau\alpha$ for a single glazed collector where τ is the glazing solar transmission and α is absorber solar absorptivity.

T8 RATIO OF COLLECTOR APERTURE TO GROSS AREA (0.9)

The ratio of the collector aperture area (i.e. window area) to the gross area. Typically this value is usually close to 0.9, actual values can be obtained from collector data sheets.

T9 COLLECTOR FLOW CHANNEL HEIGHT (MM) (6)

The spacing between the upper and lower absorber plate in millimetres. For a curved upper absorber use the average spacing. In general decreasing the flow channel height increases the collector F_R although this will result in a higher collector pressure drop.

T10 COLLECTOR FLOW CHANNEL LENGTH PER COLLECTOR (M) (1)

The distance or length that the air stream is in contact with the absorber plate for one collector. In most collectors this will be the length of collector in the flow direction. In some cases, however, collectors are designed so that the contact length is much shorter than the collector such as in the overlapped glass plate collector.

Heating Load Data

L1 BUILDING HEAT LOSS COEFFICIENT (W/C) (300.)

The heat loss coefficient or "UA" of the building. Section 3.3 gives a method of estimating this parameter.

L2 MINIMUM DAYTIME BUILDING TEMPERATURE (C) (20.)

The minimum allowable temperature of the building during the day (i.e. the furnace thermostat set point).

L3 MINIMUM NIGHTTIME BUILDING TEMPERATURE (C) (16.)

The minimum allowable temperature of the building during the night (i.e. the furnace thermostat set point at night).

L4 MAXIMUM ALLOWABLE BUILDING TEMPERATURE (C) (25)

The maximum desired building temperature. That is the temperature above which the building's occupants would be uncomfortable.

L5 BUILDING THERMAL CAPACITANCE (MJ/C)

The thermal or heat capacitance of the building. Most buildings have a thermal capacitance of 0.1 MJ/C for every square metre of floor area, although full warehouses would be slightly higher.

L6 DAILY INTERNAL HEAT GAIN (KJ/DAY) (3000)

The average daily internal heat gains from lights, people and solar gains through windows in KJ.

L7 HOURLY INTERNAL HEAT GAIN PROFILE (PERCENT)

24 hourly values of the percent of the daily internal heat gain occurring within that hour. The first value is for the hour 12 midnight to 1 a.m.

3.2 Weather Data

At present there is weather data for 46 cities that can be used by the program. These cities are tabulated below. The solar radiation data as supplied by Atmospheric Environment Service is of two types: derived or measured. Measured data is as recorded by their monitoring equipment (with missing data estimated from the previous day's values). Derived data is predicted by using other meteorological data such as rainfall, cloud cover etc.

City	Province	Latitude (Deg.)	Year	Solar Rad. Derived/Measured
Victoria	B.C.	48.7	1971	D
Prince George	B.C.	53.9	1974	M
Vancouver	B.C.	49.2	1971	M
Summerland	B.C.	49.6	1971	D
Frobisher Bay	N.W.T.	63.8	1975	D
Resolute	N.W.T.	74.7	1971	M
Edmonton	Alta.	53.6	1971	M
Medicine Hat	Alta.	50.0	1971	D
Uranium City	Sask.	59.6	1971	D
Swift Current	Sask.	50.3	1971	D
Saskatoon	Sask.	52.2	1971	D

Churchill	Man.	58.8	1975	D
Brandon	Man.	49.9	1971	D
Winnipeg	Man.	49.9	1971	M
The Pas	Man.	53.8	1971	M
Thunder Bay	Ont.	48.4	1971	D
Sault Ste. Marie	Ont.	46.5	1971	D
Sudbury	Ont.	46.5	1971	D
Kapuskasing	Ont.	49.4	1966	M
Kingston	Ont.	44.2	1971	D
Muskoka	Ont.	45.0	1971	D
Windsor	Ont.	42.3	1971	D
London	Ont.	43.0	1971	D
Toronto	Ont.	43.7	1971	M
Ottawa	Ont.	45.4	1971	M
Montreal	Que.	45.5	1971	M
Sept. Iles	Que.	50.2	1974	M
Quebec	Que.	46.8	1971	D
Sherbrooke	Que.	45.4	1971	D
Riviere du Loop	Que.	47.8	1971	D
Bagotville	Que.	48.3	1971	D
Val D'Or	Que.	48.0	1971	D
Fredericton	N.B.	45.9	1971	M
Charlo	N.B.	48.0	1971	D
Chatham	N.B.	47.0	1971	D
Moncton	N.B.	46.1	1971	D
St. John	N.B.	45.3	1971	D
Charlottetown	P.E.I.	46.3	1971	D
Truro	N.S.	45.4	1971	D
Halifax	N.S.	44.7	1971	M
Sydney	N.S.	46.2	1971	D
Yarmouth	N.S.	43.8	1971	D

St. John's	Nfld.	47.6	1971	M
Gander	Nfld.	49.0	1971	D
Stephenville	Nfld.	48.5	1971	D
Goose	Nfld.	53.3	1971	M

3.3 Estimation of Building Heat Loss Coefficient

For new homes the building heat loss coefficient can be estimated by adding up the heat loss from each building wall, window and door and including an estimate of air infiltration. The ASHRAE Handbook of Fundamentals and many heating textbooks show how this can be done. This calculation is normally done for every house in order to size the furnace.

If heating bills are available it is easy to estimate the building heat loss coefficient (UA_b) using the formula

$$UA_b = \frac{11600\ FC\ \eta_f}{DD\ HV} \quad \text{(in W/°C)}$$

where FC is the fuel consumption in litres of oil, cubic metres of gas or kWhr of electricity,

η_f is the seasonal furnace efficient, typically 0.6 for oil and natural gas and 1.0 for electricity,

HV is the heating value of fuel
- oil = 25 l/GJ
- natural gas = 27 m^3/GJ
- electricity = 278 kWhr/GJ

DD is the yearly total of degree-days below 18°C in °C-days
- Vancouver - 3000
- Toronto - 4000
- Ottawa - 4600
- Fredericton - 4600
- Winnipeg - 5900
- Yellowknife - 8600

Typical values for the building heat loss coefficient are

100 W/°C super insulated home

250 W/°C average home

500 W/°C poorly insulated home.

4. DESCRIPTION OF PROGRAM OUTPUT

4.1 Thermal Analysis Results

The thermal analysis of the system is printed in monthly intervals with a yearly summary printed at the end. The results are an estimate of the system performance of a properly designed and installed system. The program cannot account for improperly insulated ductwork, fan motor failure or other system faults.

The definition of the seven monthly output values follow.

SOLAR AVAIL. (GJ)

Total solar radiation incident on the collector over the time period in gigajoules.

SOLAR COLLECT (GJ)

Solar energy converted to heat by the solar collector over the time period.

SOLAR DELIVER (GJ)

Solar energy delivered to the building that reduces the auxiliary energy consumption.

SPACE HT LOAD (GJ)

The auxiliary heat required over the time period to space heat the building if there was no solar heating system.

AUX. HEATING (GJ)

Auxiliary energy required to space heat the building over the time period when the solar heating system is used.

FAN POWER (GJ)

The electrical energy required to operate the collector fan over the time period.

MAX. TEMP (C)

The maximum building temperature over the time period. If this value is equal to the maximum allowable building temperature, then heat must have been "dumped" from the building.

After the monthly totals have been printed, the yearly sum of the seven quantities is printed. A summary of energy use and savings is then printed in gigajoules.

The ENERGY SAVING is the percent reduction in auxiliary energy use attributable to the addition of the solar heating system i.e. percent solar. It is defined as

$$\text{Energy Saving (\%)} = \frac{100\ (\text{Space Heating Load} - \text{Aux. Heating} + \text{Fan Power})}{\text{Space Heating Load}}$$

AVERAGE SYSTEM EFFICIENCY (%) is the solar contribution divided by the solar radiation over the simulation period. It is important to note that if the daily air flow schedule is very short this value will be low regardless of the collector performance curve.

SOLAR CONTRIBUTION PER SQUARE METRE is the solar contribution divided by the collector area over the simulation period. A good application of a zero storage solar space heating system would have a value of over 1.0 GJ/m^2/yr.

5. PROGRAM ALGORITHM

5.1 Overview of Program Operation

The ZEROAIR computer program calculates the performance of zero storage solar space heating systems on an hour-by-hour basis. The basic assumption of the program is that for the purpose of calculating performance all variables, including solar radiation, ambient temperature and building heat loss can be considered constant for each hour.

The program calculation flow chart is shown in Figure 2. The first step in the program is the input and modification of the program parameters in an interactive manner. Section 3 gives a full description of the input parameters.

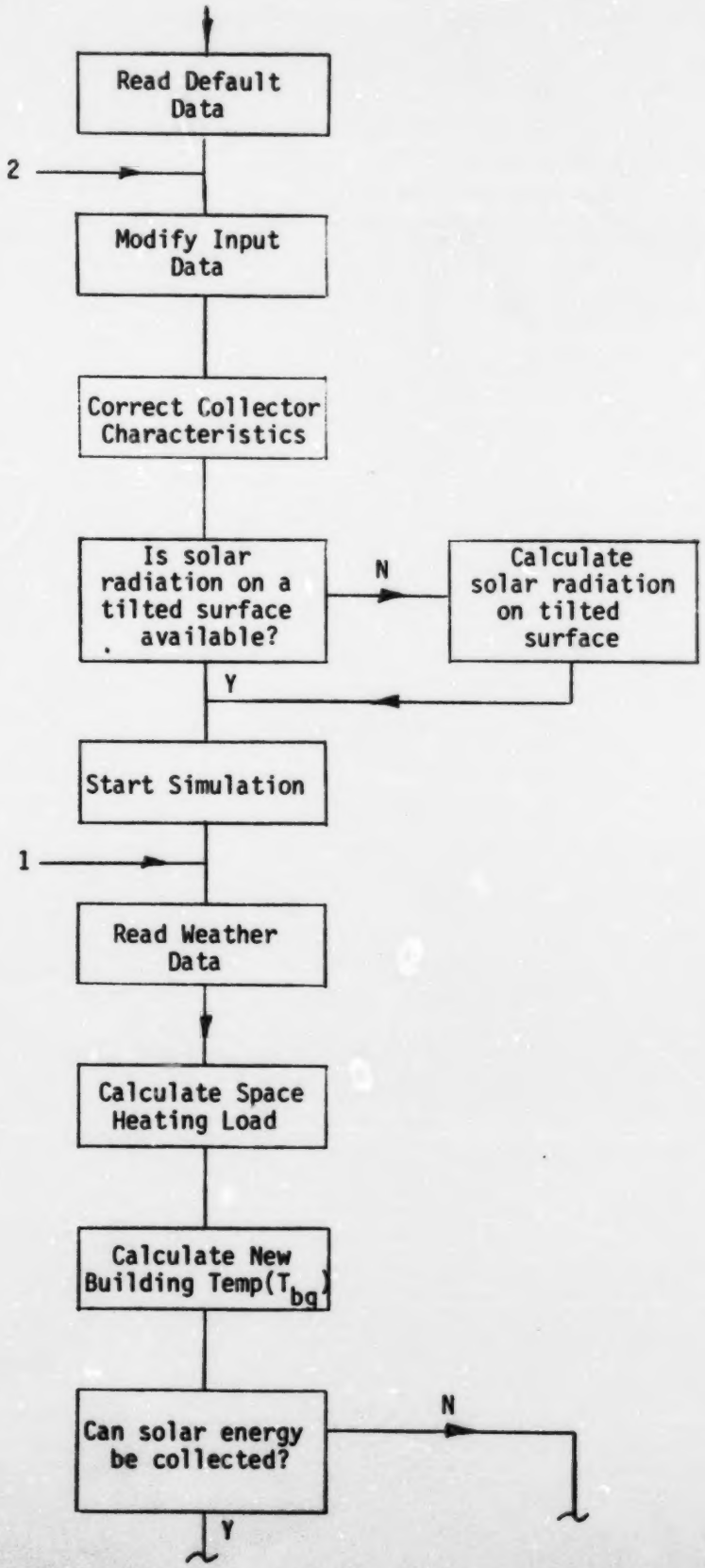
After all the parameters have been entered, the program calculates the collector heat removal factor for the test values of flow rate and flow path length using the method given in Section 5.2. This value is compared to the value of F_R found from the collector $F_R\tau\alpha$ term. The two values are printed at the terminal. At the test condition, the calculated value of F_R will be either higher or lower than the test value. If the difference between the values is greater than 20% the program prints a warning and returns to the input mode. The collector heat removal factor is then adjusted for the system flow rate, flow path length and duct air leakage. The algorithm for adjusting the collector characteristics is given in Section 5.3.

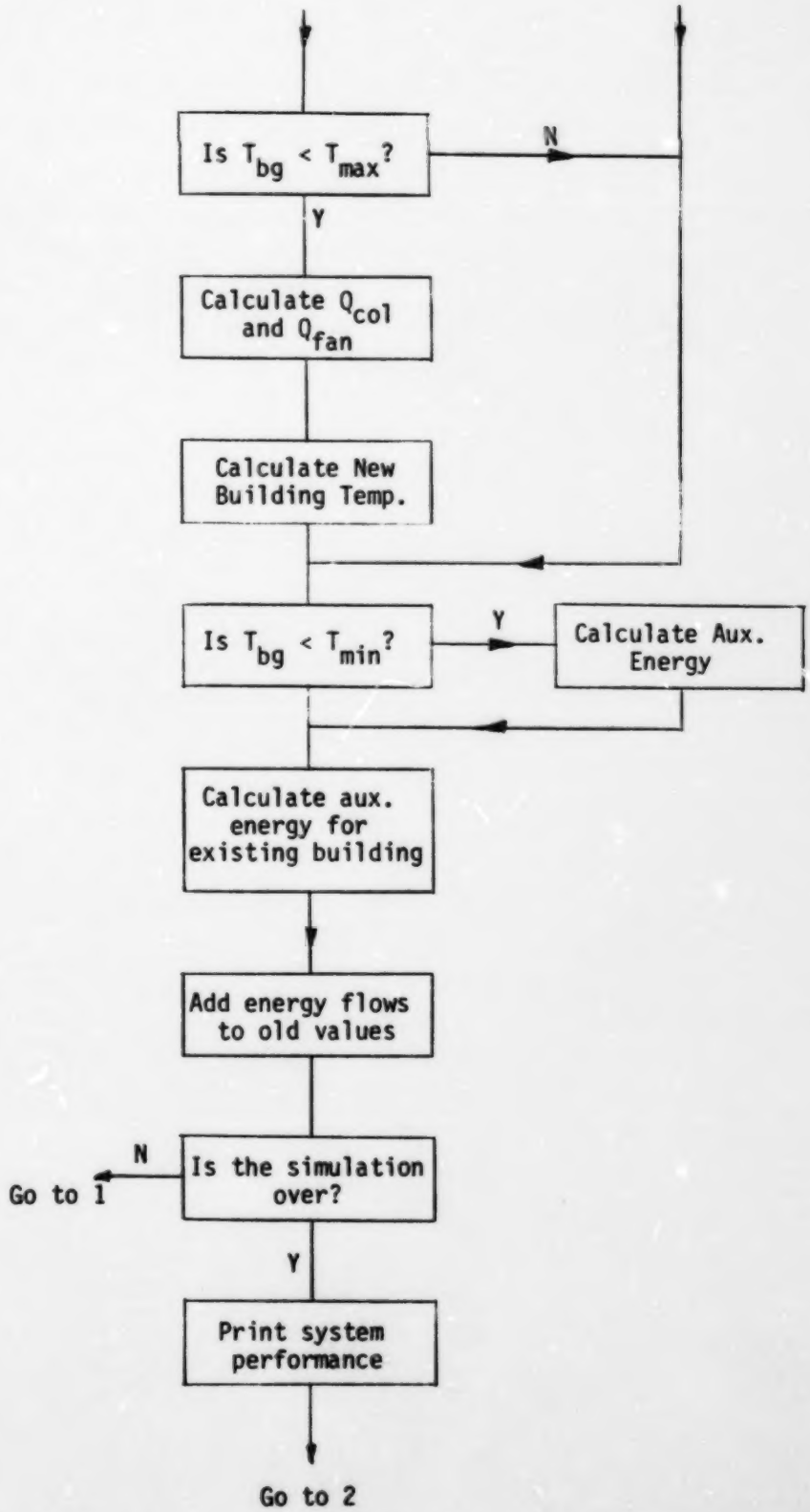
If the collector slope or azimuth is different from the value used to calculate the solar radiation in the scratch file then the solar radiation on a tilted surface is recalculated. The algorithm for performing this calculation is given in Section 5.4.

When the solar radiation and the input parameters are correct, the program begins the simulation. The first step is to calculate the building heat loss for that hour

$$Q_{bg} = UA_b\ (T_{bg} - T_a) - Q_{ig}$$

Figure 2: ZEROAIR Program Flow Chart




Is $T_{bg} < T_{max}$?
N
Y
Calculate Q_{col} and Q_{fan}
Calculate New Building Temp.
Is $T_{bg} < T_{min}$?
Y
Calculate Aux. Energy
Calculate aux. energy for existing building
Add energy flows to old values
Is the simulation over?
N
Go to 1
Y
Print system performance
Go to 2

If there was no other energy input to the building, the building temperature would become

$$T'_{bg} = T_{bg} - Q_{bg}/C_{bg}$$

Provided that this new value is below the maximum allowable temperature and heat can be collected, the solar heat delivered to the building can be calculated

$$Q_s = [F_R\tau\alpha\ K\ H_T - F_R U_L (T_{bg} - T_a)]\ A$$

where K is the incidence angle modifier factor

$$= 1 + b_o(1/\cos\theta - 1.)$$

The new building temperature is then

$$T''_{bg} = T'_{bg} + Q_s/C_{bg}$$

If this building temperature is greater than the maximum allowable temperature, then all the solar heat for that hour is not usable. The amount of solar heat that is usable is given by

$$Q'_s = Q_s\ (T_{max} - T'_{bg})\ /\ (T''_{bg} - T'_{bg})$$

If the building temperature is below the minimum allowable temperature then auxiliary energy is used to raise the temperature.

The building heating load (i.e. how much auxiliary energy is required to heat the building without the solar heating system) is calculated in the same manner as above, but without any solar gains. It should be noted that the yearly building heating load is <u>not</u> the sum of the hourly building heat losses from the solar heated building. The solar building will be at a higher temperature and thus have higher heat losses than the building with no solar system. Since we are interested in the energy savings as a result of installing

a solar heating system, our base energy consumption should be that of the existing or non-solar building.

The hourly values of the above energy flows are summed and monthly and yearly totals printed. A full description of the output is given in Section 4.

5.2 Algorithm for the Calculation of F_R

Two separate algorithms are used for the calculation of F_R, one for parallel plate solar collectors and one for fibre matrix solar collectors. It is important to note that a correction on F_R for the number of collectors in series is not necessary provided that the mass flow per unit area is kept constant.

i) F_R for Parallel Plate Solar Collectors

F_R is given by:

$$F_R = \frac{\dot{m}\ Cp}{U_L}\ (1 - \exp(-F'U_L/(\dot{m}\ Cp)$$

where $F' = U_o/(U_o + U_L)$

All of the variables are constant except for $\dot{m}$ (mass flow rate per unit area) and U_o (the total plate to fluid heat transfer coefficient). $\dot{m}$ is given each hour by the air flow rate schedule, thus, a new value of U_o must be calculated for each hour. U_o depends on the collector design.

The equations for U_o given below were taken from:

Hollands, K.G.T. and Shewen, E.C., Journal of Solar Energy Engineering, Vol. 103, No. 4, November, 1981. "Optimization of Flow Passage Geometry for Air-Heating, Plate-Type Solar Collectors".

$$U_o = h_{pf} + h_{pf} \cdot h_r/(h_r + h_{pf})$$

where h_r is the radiative heat transfer coefficient between the upper and lower absorber plates

if we assume that the inside of the air channel is painted black:

$$h_r = \sigma(T_1^2 + T_2^2)\,(T_1 + T_2)/(1.222)$$

where T_1 and T_2 are the temperatures of the upper and lower absorber plates

h_{pf} is the convective heat transfer coefficient between the plate and the air stream

$$h_{pf} = Nu \cdot k/(2.b)$$

where K is the conductivity of air

b is the spacing between the upper and lower absorber plates

Nu is the Nusselt number.

for Re < 2000 (Reynolds number)

$$Nu = 5.385 + 0.148 \cdot Re \cdot b \cdot n/L$$

where n is the number of air flow passage channels (typically equal to 1)

L is the collector flow path length

for 2000 < Re < 10000

$$Nu = 0.00044 \cdot Re^{1.2} + 9.37 \cdot Re^{0.471} \cdot b \cdot n/L$$

for 10000 < Re ≤ 100000

$$Nu = 0.03 \cdot Re^{0.74} + 0.788 \cdot Re^{0.74} \cdot b \cdot n/L$$

where $Re = \frac{2\,\dot{m}\,L}{\mu}$

if Re is greater than 100000 the program sets Re equal to 100000.

ii) F_R for Fibre Matrix Collectors (see Figure 3)

The estimation of F_R for fibre matrix collectors requires a different formulation for F_R. F_R can be though of as the ratio of the actual useful

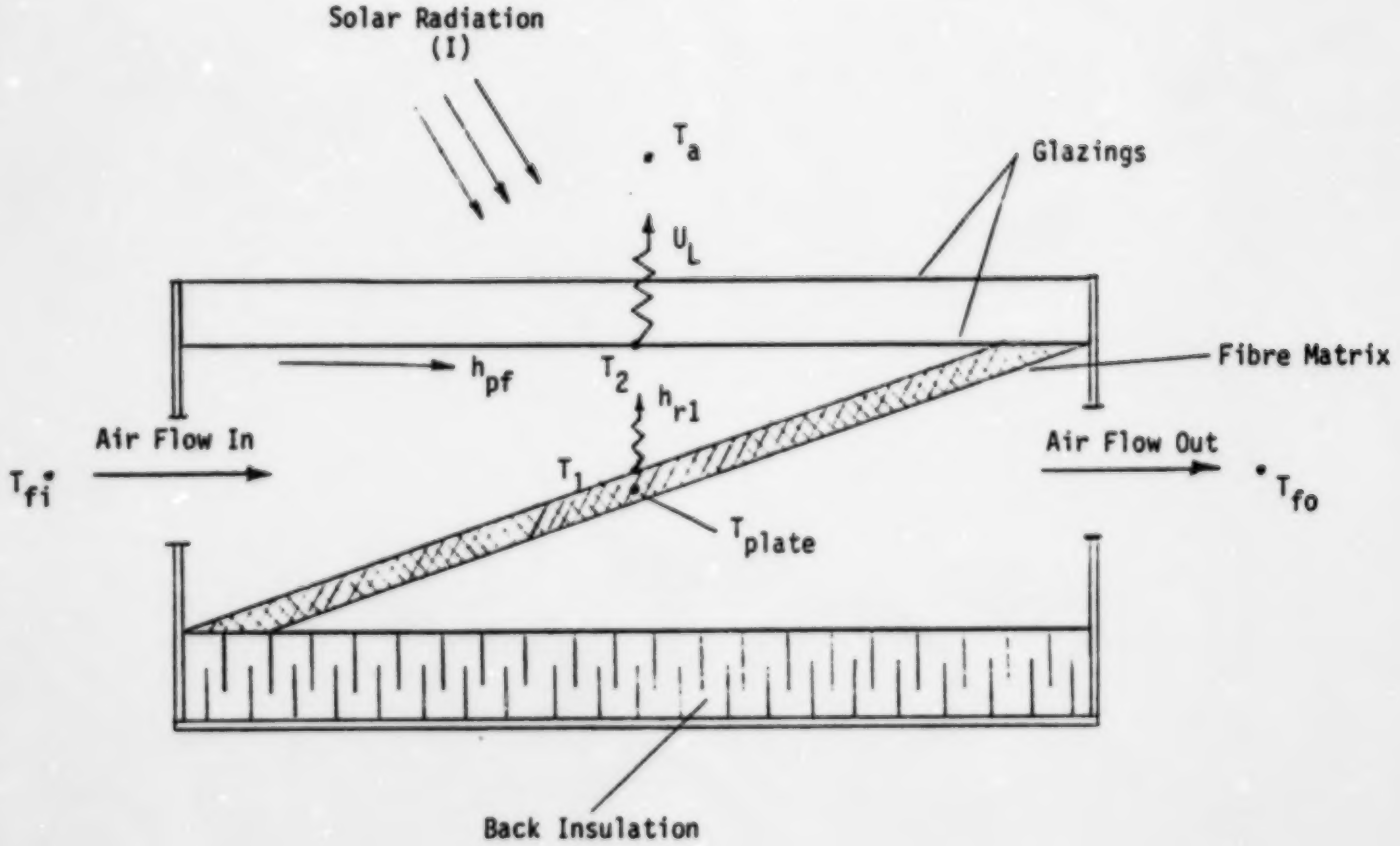


Figure 3: Schematic of Fibre Matrix Solar Collector

energy to the useful energy if the absorber plate were at the fluid inlet temperature (T_{fi}). For a ventilation collector F_R is:

$$F_r = \frac{\tau\alpha.I - U_L(T_{ave} - T_{fi})}{\tau\alpha.I - U_L(T_{fi} - T_{fi})} = 1 - \frac{U_L(T_{ave} - T_{fi})}{\tau\alpha.I}$$

where T_{ave} is the average temperature that the collector loses heat at. This temperature is normally the average plate temperature, however, a fibre matrix collector has inlet air blowing across the lower glazing thus loses heat from a lower temperature. For a fibre matrix collector T_{ave} is:

$$T_{ave} = (h_r\, T_{plate} + h_{pf}\, T_{fi})/(h_r + h_{pf})$$

where h_{pf} is the convective heat transfer coefficient between the lower glazing and the air stream

h_r is the radiative heat transfer coefficient between the fibre matrix and the lower glazing. Because of the nature of the fibre matrix, h_r is a weighted average of the value of h_r for each layer of fibres with the top layer having a weighting of 1 and the bottom layer having a weighting of 0. By integrating the values for h_r over the depth of the matrix, h_r can be approximated by:

$$h_r = h_{r1}/3 + h_{r2}/6$$

where $h_{r1} = \sigma(T_1^2 + T_2^2)\,(T_1 + T_2)/1.222$

$h_{r2} = \sigma(T_{fo}^2 + T_2^2)\,(T_{fo} + T_2)/1.222$

T_1 is the temperature of the top of the fibre matrix

T_2 is the temperature of the lower glazing

The average fibre matrix plate temperature can be calculated by:

$$T_{plate} = T_{fm} + Qu/U_o$$

where U_o is the fibre matrix to air heat transfer coefficient

T_{fm} is the average fluid temperature.

Estimating U_o for fibre matrix collectors is much more difficult than for parallel plate collectors. The reference used for these equations is:

Kays, W. and London, A.L., Compact Heat Exchangers Second Edition, McGraw-Hill, New York, 1964, pg. 129.

For fibre matrices Kays and London give equations of the form:

$$U_o = x \left(\frac{A_{fm}}{A_c}\right) \cdot \dot{m}\, Cp \;/\; (Re^{y} \cdot Pr^{2/3})$$

where Pr is the Prandtl number

where x and y are constants dependent on the type and shape of the matrix.

For a similar type of fibre matrix Kays and London give:

$x = 1.3 \qquad y = 0.45$

By knowing the average fibre matrix diameter and the fibre matrix mass, the ratio of heat transfer to collector area can be calculated. For the Amherst collector

$$\frac{A_{fm}}{A_c} \approx 80.$$

5.3 Algorithm to Correct for Collector Loop Air Leakage

All ductwork leaks air. While air leakage is not critical for indoor ductwork, it can seriously decrease performance for outdoor ductwork. The collector performance characteristics can be modified to account for this decrease in performance. The algorithm used in the program is taken from reference 1 with extensions for the case of air leaking out of the collector loop. It will be assumed that air leaks are evenly divided between the ductwork

before the collector and the ductwork after the collector.

There are four possible cases for air leakage: air leaks in before collector, air leaks in after collector, air leaks out before collector, air leaks out after collector. Each of these cases is discussed below.

(i) Air Leaks In Before Collector

In this case air leaks into the collector and out of the building. The extra heat lost out the building can be included in the $F_R U_L$ term as follows

$$F_R U_{L_{leaks}} = F_R U_L (1 - L_R) + \frac{L_R \dot{m} Cp}{A_c}$$

where L_R is the ratio of the leakage rate to the collector flow rate

In this case the full air flow goes through the collector so there is no change in the F_R or the $F_R\tau\alpha$ term.

(ii) Air Leaks In After Collector

This case is similar to case (i) except that some of the air does not flow thorugh the collector. Thus the collector heat removal factor must be adjusted for this lower flow rate. For small changes in mass flow rate

$$F'_R = F_R \left(\frac{1 - L_R}{X}\right)\left[1 - (1-X)^{\frac{1}{1-L_R}}\right]$$

$$\text{where } X = \frac{F_R U_L A_c}{\dot{m} Cp}$$

Thus the collector characteristics are

$$F_R U_{L_{leaks}} = F_R U_L \left(\frac{F'_R}{F_R}\right) + \frac{L_R \dot{m} Cp}{A_c}$$

$$F_R\tau\alpha_{leaks} = F_R\tau\alpha \left(\frac{F'_R}{F_R}\right)$$

Combining cases (i) and (ii) gives the collector characteristics for air leakage before and after the collector

$$F_R U_{L_{leaks}} = F_R U_L \left(\frac{F'_R}{F_R}\right) (1 - L_R) + 2L_R \frac{\dot{m}\, Cp}{A_c}$$

$$F_R\tau\alpha_{leaks} = F_R\tau\alpha\left(\frac{F'_R}{F_R}\right)$$

where L_R is one half the ratio of the air leakage rate to collector flow rate and F'_R is calculated based on one half the leakage rate

(iii) Air Leaks Out Before Collector

If air leaks out of the collector loop, then air must leak into the building. In this case a reduced flow rate goes through the collector and the air exhausted to the outdoors is at room temperature. This case has the same effect on collector characteristics as in case (ii).

(iv) Air Leaks Out After Collector

This case is similar to case (i) except that the air exhausted to the outdoors is at the collector outlet temperature as opposed to the building temperature. The collector characteristics for this case are

$$F_R\tau\alpha_{leaks} = F_R\tau\alpha(1 - L_R)$$

$$F_R U_{L_{leaks}} = F_R U_L (1 - L_R) + \frac{\dot{m}\, Cp\, L_R}{A_c}$$

Combining cases (iii) and (iv) gives the case of equal air leaks out before and after the collector.

$$F_R U_{L_{leaks}} = F_R U_L \left(\frac{F'_R}{F_r}\right)(1 - L_R) + \frac{2L_R \dot{m} Cp}{A_c}$$

$$F_R\tau\alpha_{leaks} = F_R\tau\alpha\left(\frac{F'_R}{F_R}\right)(1 - L_R)$$

where L_R is one half the ratio of the air leakage rate to collector flow rate and F'_R is calculated based on one half the leakage rate

5.4 Algorithm to Process Weather Data

Most Canadian weather stations measure only total solar radiation on a horizontal surface. Most solar collectors, however, are tilted toward the sun to increase the incident solar radiation. The program determines hourly values of total solar radiation (beam, diffuse and reflected) on a tilted surface and stores the values in a scratch file. The algorithm for converting horizontal solar radiation to tilted solar radiation is similar to the method used in "Solar Engineering of Thermal Processes" by Duffie and Beckman (2).

In order to estimate the solar radiation on a tilted surface it is necessary to split the total measured horizontal solar radiation into its two components: beam and diffuse. It is possible to estimate the amount of diffuse solar radiation from the ratio of the measured solar radiation to the extraterrestrial solar radiation. If this ratio is low then the solar radiation must be mostly diffuse; if this ratio is high the solar radiation must be mostly beam.

When the beam and diffuse solar radiation components are known, standard geometric relations can be used to estimate the solar radiation components on a tilted surface. When estimating solar radiation on a tilted surface a third component is introduced: reflected radiation. Reflected radiation can be estimated from the beam radiation and the ground albedo or reflectivity.

The program equations and execution procedure are given below.

At the start of each day the solar constant and the earth's solar declination are calculated. The solar constant is given by:

$$S_c = 4871.0\ (1. + 0.33\ \cos(2\pi N/365) \qquad \text{in KJ/(hr·m}^2\text{)}$$

where N is the day number (Jan 1 is 1).

The earth's declination is given by:

$$\delta = \frac{23.45 * 2\pi}{360}\ \sin\left(\frac{2\pi}{360}(284 + N)/365\right) \qquad \text{(in radians)}$$

These values are assumed constant for each day. All other calculations are made on an hourly basis.

The first step is to read the measured weather values from the data file. For each hour the weather data file contains six values in the following order.

1) month number (1-12)
2) day number (1-31)
3) hour number (1-24)
4) ground reflectivity
5) solar radiation on a horizontal surface (in Watts/m²)
6) ambient temperature (in °C)

The extraterrestrial solar radiation on a horizontal surface is calculated by:

$$H_{ex} = S_c \cdot \cos(\theta_z)$$

where $\cos(\theta_z)$ is cosine of the zenith angle (angle between the beam and the vertical)

$$\cos(\theta_z) = \cos(\phi)\ \cos(\delta)\ \cos w + \sin\phi\ \sin\delta$$

ϕ is the latitude of the location

w is the hour angle.

The diffuse solar radiation (H_d) can be estimated using a correlation by Orgill and Hollands (3).

$$H_d = 0.1769\ H \qquad \text{if } 0.75 < K_T$$

$$H_d = (1.55699 - 1.84013 \cdot K_T)\ H \qquad \text{if } 0.35 \leq K_T \leq 0.75$$

$$H_d = (1. - 0.248857 \cdot K_T)\ H \qquad \text{if } 0.0 \leq K_T \leq 0.35$$

where H is the measured hourly solar radiation

K_T is the ratio of measured solar radiation to the extraterrestrial solar radiation
$= H / H_{ex}$

The beam radiation (H_b) is simply the total measured solar radiation minus the diffuse radiation.

$$H_b = H - H_d$$

The next step is to calculate the ratio of beam radiation on the tilted surface to that on the horizontal surface (R_b).

$$R_b = \cos(\theta_T) / \cos(\theta_z)$$

where $\cos(\theta_T)$ is the cosine of the angle of incidence of beam radiation, between the beam and the normal to the surface.

$$\cos(\theta_T) = \sin(\delta)\sin(\phi)\cos(s) - \cos(\delta)\cos(\phi)\cos(s)\cos(w) + \cos(\delta)\sin(\phi)\sin(s)\cos(\gamma)\cos(w)\cos(\delta)\sin(s)\sin(\gamma)\sin(w)$$

γ is the azimuth angle measured from south (east is positive, west is negative)

Thus, the beam solar radiation on the tilted surface is

$$H_{bT} = R_b \, H_b$$

The diffuse solar radiation component on the tilted surface is estimated using the radiation view factor from the collector to the sky with correction factors for non-uniform distribution of diffuse radiation.

The correction factors for anisotropic diffuse radiation are taken from Temps and Coulson (4) and Klucher (5). The resulting equation is:

$$H_{dt} = \left(\frac{1 + \cos(s)}{2}\right) \left(1 + F \sin^3(s/2)\right) \left(1 + F \cos^2(\theta_T) \cdot \sin^3(\theta_z)\right) H_d$$

where $F = 1 - (H_d/H)^2$

The reflected solar radiation on the tilted surface (H_r) is

$$H_r = \left(\frac{1 - \cos(s)}{2}\right) \rho \, H$$

where ρ is the ground reflectivity

The total solar radiation on the tilted surface (H_T) is the sum of the beam diffuse and reflected solar radiation components.

Hourly values of total solar radiation on a tilted surface, ambient temperature, day number and hour number are written to the scratch file. When all the data has been processed and written to the scratch file, the file is rewound to be ready for the system simulation.

6. PROGRAM STRUCTURE

The program structure is described in this section. Only those individuals interested in modifying the program need read this section.

The program flow chart is shown in Figure 4. The program consists of a mainline and three subroutines:

1) MAINLINE - contains the interactive front-end for reading and modification of system data,
2) WEATH - subroutine for converting measured horizontal solar radiation to the tilted surface,
3) ZERO - subroutine to calculate system performance on an hourly basis,
4) FRCALC - subroutine to calculate the collector heat removal factor F_R for a given flow rate.

Six file definitions must be made before the program can be run:

Terminal (Read) - (Unit 5) is the device used for data input. The program will send all questions and prompts to this device.

Printer - (Unit 7) is the device that receives the printed output (i.e. a printer). If a send and receive printer is being used unit 7 need not be defined.

Weather Data - (Unit 1) is the file containing the TRNSYS compatible weather data. The data must be written in the format (2X, I2, 2X, I2, 2X, I2, F3.1, I3, F6.1) and contain month number, day number, hour number, ground reflectivity, ambient temperature (°C), and solar radiation on a horizontal surface (W/m^2).

Processed Data - (Unit 19) is the file that is created by the program containing the solar radiation on the tilted surface and ambient temperature.

Terminal (Write) - (Unit 6) is the device that receives questions from the program concerning the input of data.

Default Data - (Unit 4) is the file containing program default data.

The ZEROAIR program is written in FORTRAN 77. In order to compile this program on your system, it must be able to handle this improved version of FORTRAN.

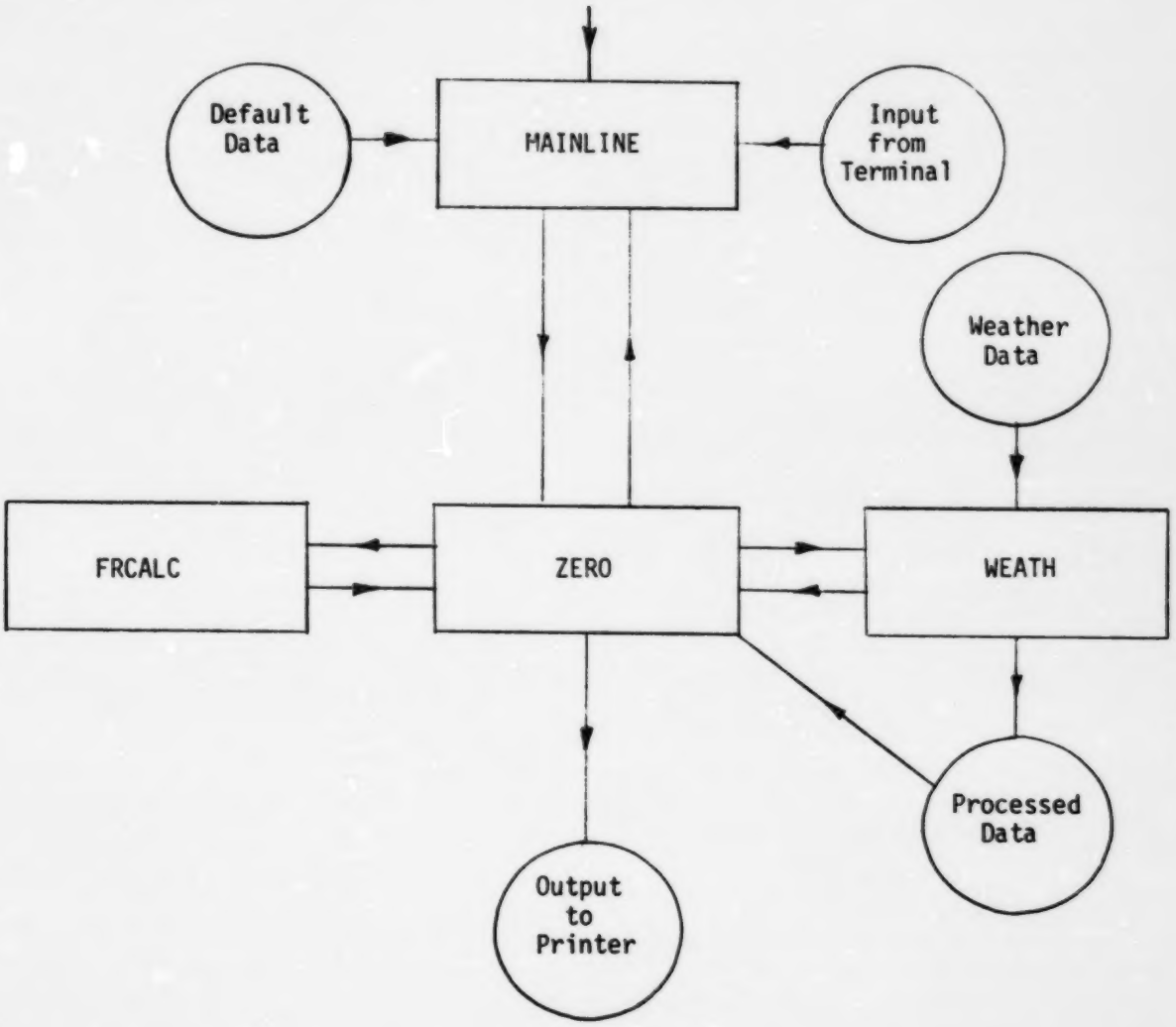


Figure 4: ZEROAIR Program Structure

7. REFERENCES

1. Mitchell, J.C. et al., FCHART 4.0 User's Manual, University of Wisconsin-Madison, EES Report 50, September 25, 1980.

2. Duffie and Beckman, Solar Engineering of Thermal Processes, John Wiley and Sons, New York, 1980.

3. Orgill, J.F. and Hollands, K.G.T., Solar Energy, Vol. 19, No. 2, "Correlation Equation for Hourly Diffuse Radiation on a Horizontal Surface".

4. Temps, R.C. and Coulson, K.L., Solar Energy, Vol. 19, No. 2, "Solar Radiation Incident upon Slopes of Different Orientation".

5. Klucher, T.M., Solar Energy, Vol. 23, No. 2, "Evaluation of Models to Predict Insulation on Tilted Surfaces".

8. NOMENCLATURE

A	total collector area
A_c	area of one collector
A_{fm}	surface area of fibre matrix
b	collector channel height
C_{bg}	thermal capacitance of the building
Cp	specific heat
F'	$U_o/(U_o + U_L)$
F_R	collector heat removal factor
$F_R\tau\alpha$	collector transmission-absorption coefficient
F_RU_L	collector heat loss coefficient
H	measured hourly solar radiation
H_b	beam hourly solar radiation
H_{bT}	beam hourly solar radiation on a tilted surface
H_d	diffuse hourly solar radiation
H_{dT}	duffuse hourly solar radiation of a tilted surface
H_{ex}	extraterrestrial hourly solar radiation
hpf	plate to fluid convective heat transfer coefficient
h_r	radiative heat transfer coefficient
H_r	reflected hourly solar radiation
H_T	solar radiation on the tilted surface
I	total incident solar radiation
K_T	clearness index
L	length of collector in flow direction
L_R	ratio of collector loop air leakage to collector flow rate
$\dot{m}$	mass flow rate
n	number of air flow passage channels
N	day number of the year
Nu	Nusselt Number
Q_{bg}	building heat loss
Q_{ig}	internal heat gains due to lights, people and windows
Q_S	solar heating contribution
R_b	ratio of beam radiation on tilted surface to horizontal surface

R_e	Reynolds Number
s	collector slope
S_c	solar constant
T_1, T_2	temperature of upper and lower plates of the air channel
T_a	ambient temperature
T_{ave}	average temperature that collector losses heat from
T_{bg}	temperature of building
T_{fi}	collector fluid inlet temperature
T_{fm}	average collector fluid temperature
T_{fo}	collector fluid outlet temperature
T_{in}	inlet temperature to the building
T_{plate}	average temperature of the collector absorber plate
U_L	collector heat loss coefficient
U_o	total plate to fluid heat transfer coefficient
x	matrix constant
y	matrix constant

Greek Symbols

α	solar absorptivity
δ	solar declination
γ	azimuth angle
ϕ	latitude
π	3.14159
μ	absolute viscosity
ρ	density
σ	Stefan-Boltzman constant
ω	hour angle
$\tau\alpha$	transmission-absorption product
$(\tau\alpha)_e$	effective transmission-absorption product

9. INPUT DATA WORKSHEET

		Default Value	
C.	COLLECTOR DATA		
C1	NUMBER OF COLLECTORS	20.00	_____
C2	NUMBER OF COLLECTORS IN SERIES	1.00	_____
C3	COLLECTOR SLOPE (DEGREES)	45.00	_____
C4	COLLECTOR ORIENTATION (SOUTH=0,EAST=+, DEG.)	.00	_____
C5	COLLECTOR FLOW RATE PER UNIT AREA (L/(SEC*M2))	10.00	_____
C6	PERCENT COLLECTOR LOOP AIR LEAKAGE	5.00	_____
C7	FAN POWER CONSUMPTION PER UNIT AREA (W/M2)	10.00	_____
T.	COLLECTOR TEST DATA		
T1	GROSS AREA OF ONE COLLECTOR (M2)	2.00	_____
T2	NUMBER OF COLLECTORS IN SERIES WHEN TESTED	1.00	_____
T3	FR-TAU-ALPHA (TEST)	.80	_____
T4	FR-UL (W/(M2*C)) (TEST)	4.00	_____
T5	INCIDENT ANGLE MODIFIER	-.10	_____
T6	COLL. TEST FLOW RATE PER UNIT AREA (L/(SEC*M2))	10.00	_____
T7	TRANSMISSION-ABSORPTION PRODUCT	.90	_____
T8	RATIO OF APERTURE TO GROSS AREA	.90	_____
T9	COLLECTOR CHANNEL HEIGHT (MM)	6.00	_____
T10	COLLECTOR FLOW CHANNEL LENGTH (M)	1.00	_____
L.	HEATING LOAD DATA		
L1	BUILDING HEAT LOSS COEFFICIENT (W/C)	300.00	_____
L2	MINIMUM DAYTIME BUILDING TEMPERATURE (C)	20.00	_____
L3	MINIMUM NIGHTIME BUILDING TEMPERATURE (C)	16.00	_____
L4	MAXIMUM ALLOWABLE BUILDING TEMPERATURE (C)	22.00	_____
L5	BUILDING THERMAL CAPACITANCE (MJ/C)	15.00	_____
L6	DAILY INTERNAL HEAT GAIN (MJ/DAY)	30.00	_____
L7	HOURLY INTERNAL HEAT GAIN PROFILE (PERCENT)	100.00	

2.25	.00	.00	.00	.00	.00
1.50	4.65	7.25	8.49	6.90	4.50
3.60	5.10	2.70	2.40	2.10	3.75
6.75	11.60	9.50	6.90	5.46	4.65